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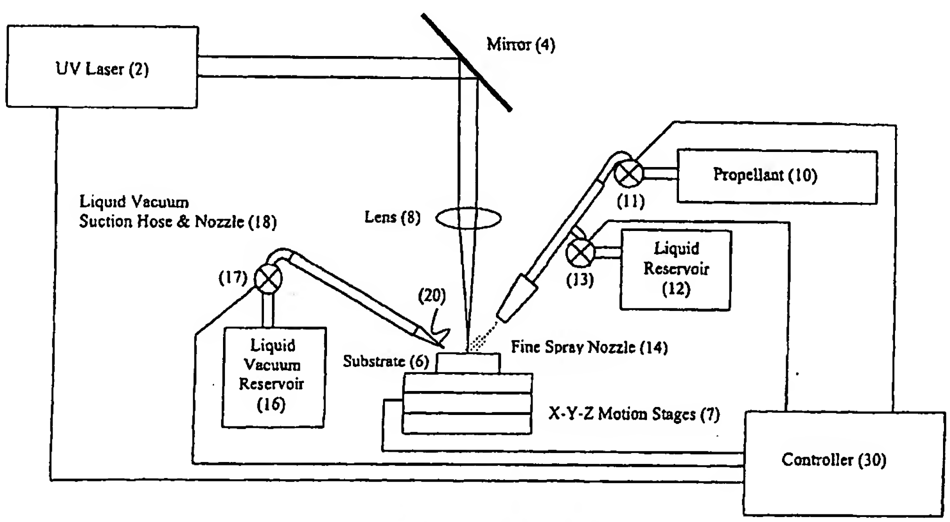
(54) Title: METHOD AND APPARATUS FOR FINE LIQUID SPRAY ASSISTED LASER MATERIAL PROCESSING



Laser Liquid Assist Apparatus

(57) Abstract: A system for liquid-assisted, laser material processing includes an ultraviolet laser (2) for emitting a laser beam, a translation stages (7) for mounting a substrate (6) for exposure to the laser beam, an imaging system for imaging the beam to the substrate (6), and a nozzle (14) coupled with a liquid reservoir (12) for propelling a fine spray of the liquid onto the substrate (6). The reservoir contains a liquid such as water that is not substantially photoabsorbing around a primary ultraviolet wavelength of the ultraviolet laser beam. The translation stages (7) are movable in at least two dimensions that are substantially in a plane of the substrate (6), such that by translating the stages a substantial surface area of the substrate (6) may be machined by exposure to the incident utltraviolet laser beam.

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METHOD AND APPARATUS FOR FINE LIQUID SPRAY ASSISTED LASER MATERIAL PROCESSING

PRIORITY

This application claims the benefit of priority to United States provisional patent applications no. 60/328,737, filed October 10, 2001, and 60/327,413, filed October 3, 2001, and this application claims the benefit of priority to United States utility patent application no. (not yet assigned), filed on October 2, 2002.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to laser material processing, and particularly to a system and method for laser etching of materials including a liquid assist.

2. Description of the Related Art

Excimer lasers have been considered poor choices as exposure radiation sources for machining metals due to the generation of severe recast and debris during the laser interaction. High repetition rate, Q-switched YAG lasers also generate a recast and debris field when machining metals. These YAG lasers may be focused to a small spot and rastered over the area to be cut so that the generation of recast and debris may be somewhat tempered. However, the generation of recast and debris using a YAG laser in this way will still not be eliminated or even suppressed below a sufficient tolerance level.

Laser etching of materials in submersed in liquid baths is described at United States patent no. 5,057,184, which is hereby incorporated by reference. In the '184 patent, the part or workpiece being etched is submersed in a liquid bath and the fluence of the laser source is kept at a relatively low level, e.g., 2.1 J/cm^2. The exposure source lasers described in the '184 patent, i.e., copper vapour, YAG and chopped CW argon ion lasers, each emit in the visible region above 400 nm. The '184 patent teaches to avoid higher fluences as recast and cracks will form.

It is recognized in the present invention that a method may be used wherein a large, perhaps unregulated amount of liquid is flowed over a sample. However, particularly at laser repetition rates such as greater than a few Hz and particulary at repetition rates above 1 kHz, such use of thick liquid flow layers, e.g., greater than 1 mm, results in high turbulence and reduced performance through refraction affects due to the interaction of the pulsed laser beam with the liquid. Still other methods may use a slow spiral trepanning for holes or multipass cuts to increase the width of the kerf. Unfortunately, this adds time to the process and generally does not eliminate the recast and debris altogether.

It is desired to have an apparatus and method for UV laser machining of workpieces such as metal substrates that does not produce an interolerable level of recast and debris.

SUMMARY OF THE INVENTION

A system for liquid-assisted, laser material processing includes an ultraviolet (UV) laser for emitting an UV laser beam, a translation stage for mounting a workpiece for exposure to the UV laser beam, an imaging system for imaging the beam to the workpiece, and a nozzle coupled with a liquid reservoir for propelling a fine spray of the liquid onto the workpiece. The reservoir contains a liquid that is not substantially photoabsorbing around a primary UV wavelength of the UV laser beam. The translation stage is movable relative to the UV laser beam in at least two dimensions that are substantially in a plane of the workpiece, such that by translating

the stage, a substantial surface area of the workpiece may be machined by exposure to the incident UV laser beam.

A method of liquid-assisted, laser material processing includes mounting a workpiece on a translation stage, generating an ultraviolet (UV) laser beam, imaging the UV laser beam onto the workpiece, propelling a fine spray of liquid onto the workpiece during exposure of the workpiece to the UV laser beam, wherein the liquid is not substantially photoabsorbing around a primary UV wavelength of the UV laser beam, and translating the workpiece on the translation stage relative to the UV laser beam in at least two dimensions that are substantially in a plane of the workpiece, such that by translating the stage, a substantial surface area of the workpiece may be machined by exposure to the incident UV laser beam.

INCORPORATION BY REFERENCE

What follows is a cite list of references each of which is, in addition to those references cited above and below, and including that which is described as background and the invention summary, hereby incorporated by reference into the detailed description of the preferred embodiments below, as disclosing alternative embodiments of elements or features of the preferred embodiments not otherwise set forth in detail below. A single one or a combination of two or more of these references may be consulted to obtain a variation of the preferred embodiments described in the detailed description below. Further patent, patent application and non-patent references are cited in the written description and are also incorporated by reference into the preferred embodiment with the same effect as just described with respect to the following references:

United States patents no. 5,057,184, 5,841,099 and 5,593,606;

Dupont et al., "Enhancement of Material Ablation Using 248, 308, 532, 1064 nm Laser Pulse With a Water Film on the Treated Surface," J. Appl. Phys. 78 (3), (1 August 1995); and

S. Zhu, et al., "Laser Ablation of Solid Substrates in a Water-Confined Environment," Applied Physics Letters, Vol. 79, No. 9 (27 August 2001).

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 schematically illustrates an apparatus for assisting laser material processing according to a preferred embodiment.

Figures 2a-2b are photographs illustrating an example of a workpiece including a region processed using a technique according to a preferred embodiment.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The preferred embodiments includes methods and systems for assisted laser material processing, and particularly for machining workpiece materials such as metals, semiconductor substrates, ceramics, glasses and polymers. A preferred apparatus includes a nozzle for propelling a fine spray or mist of a liquid such as water at the workpiece to be machined. A laser beam, preferably as may be generated by a UV laser or other source of exposure radiation generated between 190 nm and 1100 nm (for water), and is not strongly absorbed by the liquid assist, is focused to the workpiece using, e.g., a focusing lens, while the spray or mist is propelled at the workpiece creating a layer of the liquid on the workpiece surface as the beam is incident upon the workpiece to machine the workpiece.

Preferably, the liquid is propelled using a propellant such as pressurized nitrogen, helium, argon or any other non-absorbing gas for the wavelength being used and a liquid reservoir. The liquid is propelled by the pressurized gas flow through a spray nozzle to the workpiece. The spray nozzle may have an orifice between 100 – 1000 microns, such as around 300 microns, and the pressure of the spray at the nozzle may be several psi, such as between 5 - 100 psi, and specifically may be around 18 psi. Also preferably, a wet suction hose is provided for drawing the liquid from the surface of the workpiece. Alternatively, the liquid is simply allowed to run-off the workpiece and/or may be collected as it runs-off.

Also preferably, the flowing water layer is less then 100 microns thick, and may be as thin as can be maintained as a continuous sheet of liquid over the

application region, and the flowing liquid layer may be within a range between 25 – 60 microns, and more specifically between 25 – 50 microns. The area covered may be between a few square millimeters and depends on the geometry of the applied laser beam. The flow rate may be around one milliliter per minute.

A preferred method includes generating a laser beam preferably at a wavelength less than 400 nm and directing and/or focusing the beam to a workpiece for exposing and machining the workpiece, and propelling a liquid, and preferably a non-absorbing liquid such as water, at the workpiece for creating a thin layer of the liquid on the surface of the workpiece to be processed by the UV beam. The propelling operation is preferably begun prior to or coincident with the exposing of the workpiece with the UV beam. A wet vacuum operation is preferably also performed while the liquid is being propelled to the workpiece.

Figure 1 generally illustrates an apparatus for assisting laser material processing according to a preferred embodiment. Referring now to Figure 1, a preferred apparatus includes an exposure source 2 such as a UV laser for generating a beam of radiation at wavelengths less than 400 nm, although longer wavelength radiation sources may be used and may benefit from use with the preferred embodiments. The repetition rate may be as low as a few Hz or may be operated in cw mode, although operating at higher repetition rates such as 1 kHz or more, the low thickness water layer preferred herein is particularly advantageous as producing significantly low turbulence and greatly improving the peformance of the device, e.g., as compared with a device wherein a flow liquid layer has a thickness of one millimeter or more. A mirror 4 is shown for redirecting the UV beam toward a workpiece 6 such as a metal, semiconductor, ceramic, glass or polymer substrate. The radiation is preferably focused onto the workpiece 6 by a focusing or imaging lens 8.

Figure 1 also generally shows a device including a propellant 10, propellant gas valve 11, a liquid reservoir 12, a liquid valve 13 and a fine spray nozzle 14. The fine spray nozzle may be any of a variety, and an exemplary nozzle has an orifice of 300 microns and a nozzle pressure of 18 psi, although greater or smaller nozzle orifices and nozzle pressures may be used. A flow rate on the workpiece may be produced at around one milliliter per minute, although the flow rate will depend on

the workpiece area and will increase if the speed of the liquid is faster for some reason perhaps depending on the configuration of the workpiece, such as may depend on how much gravity is allowed to be involved, as well as the nozzle pressure or propellant speed.

The preferred device schematically shown in Figure 1 is configured such that as the propellant 10, such as nitrogen gas, is propelled under pressure through the device for expulsion through the nozzle 14, liquid, such as water, alcohols, or other non laser wavelength-absorbing liquid, is expelled from the device with the propellant 10 through the fine spray or mist nozzle to be incident on the surface of the workpiece 6 to be machined by the UV beam. The liquid then flows over the workpiece region to be processed. The flowing liquid layer has preferably a substantially uniform thickness of less than 100 – 200 microns, and particularly between 25 and 60 microns, but may be a few hundred microns depending on the liquid being used and ability to obtain uniform flow at a minimal flow layer thickness. The flowing liquid layer area may be 1 – 100 square millimeters, and particularly around 25 mm^2, and will depend on the area of the application beam. The flowing liquid may be channeled such as by provided walls around the application workspace, e.g., using 60 micron thick tape or perhaps greater if the flow layer thickness is somewhat greater than 60 microns, or shims or other material. The shaping of the flow using the channeling may be advantageous in providing improved uniformity of the flow of the non-photoabsorbing liquid.

Figure 1 further generally shows a vacuum device including a liquid vacuum reservoir 16, a vacuum valve 17 coupled to a liquid vacuum suction hose and nozzle 18, which includes a motor or other device for creating a suction at the nozzle end 20. The nozzle end 20 is disposed near the surface of the workpiece for wet vacuuming the liquid from the surface of the workpiece 6 as the workpiece is machined on X-Y-Z motion stages 7 and the liquid is propelled to its surface from the fine spray or mist nozzle 14. Figure 1 further generally shows that the controller 30 controls the operation of the X-Y-Z motion stages, propellant valve 11, liquid valve 13, the vacuum valve 17 and the operation of the laser 2.

In particular, the UV laser 2 may be a frequency tripled Nd:YAG (355 nm) or other solid state laser apparatus directly emitting or frequency-multiplied to emit an ultraviolet beam, and the UV laser may generate another sub-400 nm wavelength such as may be emitted by an excimer laser, in particular XeF emitting at 351 nm, XeCl emitting at 308 nm, KrF emitting at 248 nm and ArF emitting at 193 nm, or a VUV molecular fluorine laser emitting at 157 nm, or even an EUV generating source such as may be used to generate radiation around 11 nm to 15 nm, and generally an exposure source generating radiation at wavelengths less than 400 nm, although even a longer wavelength exposure source may be used in an apparatus that would benefit according to the preferred embodiments herein. The preferred UV beam may be advantageously applied to an inorganic material with a fluence of more than approximately 2 J/cm^2. Although as mentioned, this process is not limited to use with UV lasers or exposure sources having wavelength less than 400 nm, but is understood as working best with UV exposure light, wherein use of a 248 nm KrF excimer laser beam is specifically preferred as exhibiting high performance.

The laser light is directed onto a sample of material to be machined, such as to be cut, grooved, drilled, etched, or otherwise to machine the workpiece 6 as understood by those skilled in the art of laser machining, using the focusing or imaging lens 8 and mirror 4. Fluences on the order of >3.5 J/cm^2 may be used to achieve very fast etch rates and high throughput. The materials best suited for use as workpieces 6 with this technique include metals such as stainless steel, cold rolled steel, nickel, brass, copper, molybdenum, and other metals that may be machined as understood by those skilled in the art, i.e., not limited to the metals mentioned above, and semiconductors such as silicon, bismuth telluride, and other semiconductors that may be machined as understood by those skilled in the art, i.e., not limited to the semiconductor materials mentioned above, as well as some insulators made of ceramic, glass and polymers. Optimum fluences for polymers when using the assist is in the range of 100 mJ/cm^2 to <1 J/cm^2. The workpiece 6 may be disposed vertically, horizontally or otherwise at any angle relative to gravity, and the UV beam is preferably normally incident at the workpiece 6, but may be somewhat offset depending on the machining application desired.

Although not shown in Figure 1, a CAD/CAM system may be used to create a desired circuit pattern that will be fabricated onto an electrically insulated material workpiece coated with the conductive metal layer. The CAD/CAM system may be used to control either or both of the shape and size of the laser beam as it interacts with the liquid film on the printed circuit substrate with metal coating. The laser energy would be preferably adjusted to just above the ablation threshold (e.g., 2 to 3 J/cm^2) of the metal being machined, while liquid assist is applied. The speed of the stages, or rastering of the laser beam, would also be controlled by the CAD/CAM system so that the metal etching is removed or exposed, but minimally etches into the insulating substrate. The workpiece may be preferably positioned on a motion stage, and preferably X-Y-Z motion stages.

A fine spray or mist of liquid droplets or a thin liquid layer, and preferably a liquid of non laser wavelength-absorbing material such as, e.g., water for wavelengths between 190 and 1100 nm, is directed to the laser interaction region of the workpiece 6 as propelled from the nozzle 14 such that a fine stream of the preferred liquid forms a flow over the laser interaction region while the workpiece 6 is being machined by the beam from the UV laser 2. Generally, the thinner the stream of liquid and the more laminar the flow, the better the effect of the assist, as long as the liquid layer is not so thin that there is insufficient liquid material to achieve the purposes of these preferred embodiments. For example, a few cubic centimeters of liquid in the reservoir 12 can be used for a great deal of machining according to a preferred embodiment. The stream of liquid is preferably maintained very thin during machining in order to minimize deleterious refraction effects as the beam interacts with the liquid layer before and after impinging upon the workpiece 6.

The airbrush device including propellant 10, liquid reservoir 12 and fine mist nozzle 14, as illustrated schematically at Figure 1, is preferably disposed in close proximity to the target workpiece 6 to create the thin stream of liquid, preferably water, that approaches as close as possible a laminar flow, wherein the less turbulent the flow of the liquid is, the better. It has been observed that if the spray nozzle 14 is disposed far from the surface of the workpiece 6, then droplets may begin to be formed and the laminar flow may be deteriorated. In a particular preferred

embodiment, the fine spray nozzle 14 may be disposed such that the workpiece 6 is positioned at a "focal point" of the spray, or a point in the flow of the liquid in the spray where cross-sectional flow uniformity may be relatively high. The advantageous use of the water assist, or other preferably non laser-wavelength-absorbing liquid assist, according to the preferred embodiment herein permits production of substantially burr free laser etched features, with minimal to no deposit of ablation particulates around the laser etched area.

In cutting materials, a continuous stream of water or other liquid can be applied. A pulsed stream of this water may be used for drilling small holes or blind features. This is advantageous because as the laser beam approaches the bottom of the material of the workpiece 6, a shock wave created at the water/ laser interaction boundary may otherwise cause the material to "punch" out the back side with a resulting jagged hole. In order to avoid this effect controller 30 opens propellant gas valve 11 followed by liquid valve 13. Vacuum suction valve 17 is opened to collect the spent liquid from the fine mist nozzle 14. Controller 30 initiates the laser 2 trigger and the movement of the X-Y-Z motion stages 7. At a point just before where the liquid assist might causes break out or chipping of the substrate 6, as result of high pressures generated in the laser interaction region, the controller 30 closes the liquid valve 13. At this point the propellant gas 10 pushes the residual liquid from the laser interaction area so that no chipping or breakage will occur from shock waves generated from the laser and liquid interaction.

By using the water or other liquid assist in accordance with the preferred embodiment, substantially recast free features may be achieved, with very little, if any, debris. Moreover, the recast generated in an unassisted cut tends to block the radiation from penetrating deeper into the material, or the recast material may re-melt and adhere to the bulk material being cut. The laser material processing with water or other liquid assist according the preferred embodiment provides a clean, fast cut without these disadvantageous recasts and/or re-melts interfering with the processing and/or use of the processed workpiece 6.

The preferred embodiment may be used in many industrial applications. For example, it can be used to engrave printing plates, etch and cut medical devices such

as stents or catheters and microelectronic probes, create MEMS structures in metals and semiconductors like silicon. In non-metals, such as semiconductors, ceramics, glass and polymer insulators, it can aid in eliminating debris generated in the ablation process and therefore eliminate or reduce the time, cost and effort otherwise typically involved in a post-cleaning process. Using the liquid assist technique in polymer machining has shown not only an improvement in in the reduction of debris, but also a significant improvement in the optical resolution through the reduction of the heat-affected zone. This technique facilitates the creation of optical waveguide devices in polymers coated onto semiconductor or glass substrates or in the creation of any optical MEMS device formed from a polymer. Post processing of flexible circuits and microelectronic circuits of any type, for example, can be eliminated after they are processed by laser assisted liquid etching. The debris is washed away and no oxides remain on underlying metalization. This would further apply towards the clean removal of insulation around conductive wires or fiber optics. Contact lens or interoccular lens device cutting or trimming of flashing would equally benefit from this technique. Advantageously, the apparatus and method of the preferred embodiment have been shown to permit machining at up to at least 20 mm per minute, as compared with past techniques that have permitted only around 8 mm per minute machining using a 3 watt 355 nm Nd:YAG laser in cutting 670 micron thick silicon. Consequently, the cutting or dicing of silicon or sapphire wafers can be accomplished with minimal kerf width and little to no slag or debris on the periphery of the cuts and with fastest possible speeds. In addition, the past techniques typically have involved a clean-up process, whereas little or no clean-up may be performed in accord with the preferred embodiment.

Many different types of nozzles 14 or spray devices may be used to apply the liquid mist or fine spray to the workpiece 6. Even a continuous flow of liquid from a hose, faucet or other orifice landing on the sample may be advantageous. As the stream of water hits the sample it spreads relatively uniformly over the interaction region of the workpiece 6 and can form a thin sheet of water. As long as the stream of water does not have air bubbles, or create much turbulence when it hits the sample,

it may be advantageously used in accordance with alternative embodiments herein to produce the desired conditions.

There may be several ways to configure the system for creating the preferred thin layer of liquid at the workpiece 6. For example, the nozzle(s) 14 may be pointed at the workpiece 6 for directly depositing the liquid at the workpiece 6 as shown in Figure 1, or the nozzle(s) 14 may be directed away from the workpiece 6 so that the mist settles more gently and/or uniformly on the workpiece 6. An example of the latter arrangement would be to direct the nozzle(s) 14 to propel the liquid upward in the vicinity of the workpiece 6 allowing the mist to settle back down onto the workpiece 6. The nozzle(s) 14 may be configured with multiple openings for spreading the liquid and facilitating the creation of a mist or fine spray.

Another alternative method may be used which involves the use of some kind of "wicking" device. A piece of tissue or other thin material may be placed over the workpiece 6 and then soaked with liquid. The laser 2 would cut through the thin, liquid absorbing material and begin cutting the subject workpiece 6. The thin and saturated absorbing material would supply a continuous source of liquid to the desired area. This alternative embodiment may have the disadvantage of not producing optimal liquid flow, and in fact the flow of liquid may be quite minimal according to this embodiment, but it would have a positive advantageous effect over past systems and techniques.

A laser machining apparatus and method is described above including a nozzle connected to a pressurized gas and liquid reservoir for propelling a fine spray or mist of a liquid such as water for creating a layer of the liquid at the surface of the workpiece to be machined by exposure to a laser beam. The laser beam, preferably as may be generated by a UV laser or other source of exposure radiation, but is not strongly absorbed by the liquid assist material, is focused to the workpiece using, e.g., a focusing or imaging lens, while the fine spray or mist is propelled for creating the layer of the liquid on its surface as the beam is incident upon the workpiece for machining. Figures 2a-2b are photographs illustrating an example of a workpiece including a region processed using a technique according to a preferred embodiment.

While an exemplary drawing and specific embodiments of the present invention have been described and illustrated, it is to be understood that that the scope of the present invention is not to be limited to the particular embodiments discussed. Thus, the embodiments shall be regarded as illustrative rather than restrictive, and it should be understood that variations may be made in those embodiments by workers skilled in the arts without departing from the scope of the present invention.

In addition, in methods that may be performed according to preferred embodiments herein and that may have been described above, the operations have been described in selected typographical sequences. However, the sequences have been selected and so ordered for typographical convenience and are not intended to imply any particular order for performing the operations. For example, although it is preferred to begin the flow of the liquid across the surface of the workpiece before beginning the machining with the laser beam, the flow of liquid may be started after the machining is started, and the vacuuming may be started before or after either of the liquid flow or machining is started.

What is claimed is:

1. A system for liquid-assisted, laser material processing, comprising:

an ultraviolet (UV) laser for emitting an UV laser beam;

a translation stage for mounting a workpiece for exposure to the UV laser beam;

an imaging system for imaging the beam to the workpiece; and

a nozzle coupled with a liquid reservoir for propelling a fine spray of the liquid onto the workpiece, and

wherein the reservoir contains a liquid that is not substantially photoabsorbing around a primary UV wavelength of the UV laser beam, and

wherein the translation stage is movable relative to the UV laser beam in at least two dimensions that are substantially in a plane of the workpiece, such that by translating the stage, a substantial surface area of the workpiece may be machined by exposure to the incident UV laser beam.

2. The system of Claim 1, wherein the nozzle is directed at the workpiece.

3. The system of Claim 1, wherein the fine spray becomes a mist as the liquid settles onto the workpiece.

4. The system of Claim 1, wherein the liquid substantially comprises water.

5. The system of Claim 1, wherein the imaging system comprising a focusing lens.

6. The system of Claim 1, wherein the fine spray becomes a thin layer of the liquid flowing over an application region of the workpiece.

7. The system of Claim 6, wherein the thin layer is less than 100 microns thick.

8. The system of Claim 6, wherein the thin layer is between 25 and 60 microns thick.

9. The system of Claim 6, wherein the thin layer is between 25 and 50 microns thick.

10. The system of Claim 6, wherein the thin layer just thick enough to be maintained as a continuous sheet of liquid over the application region of the workpiece.

11. The system of Claim 6, wherein the application region comprises a few square millimeters of surface area of the workpiece.

12. The system of Claim 6, wherein the thin layer flows at a flow rate of around one milliliter per minute.

13. The system of Claim 1, wherein the nozzle is further coupled with a propellant for assisting in the propelling of the fine spray of the liquid.

14. The system of Claim 13, wherein the propellant includes a pressurized gas that is not substantially photoabsorbing around a primary UV wavelength of the UV laser beam.

15. The system of Claim 14, wherein the pressure of the pressurized gas is between 5 and 100 psi.

16. The system of Claim 14, wherein the pressure of the pressurized gas is around 18 psi.

17. The system of Claim 1, wherein the nozzle defines an orifice between 100 and 1000 microns across.

18. The system of Claim 1, wherein the nozzle defines an orifice around 300 microns across.

19. The system of Claim 1, further comprising a wet suction system for drawing the liquid from the workpiece.

20. The system of Claim 1, further comprising a collection tray for collecting the liquid as it runs off of the workpiece.

21. A method of liquid-assisted, laser material processing, comprising the steps of:

mounting a workpiece on a translation stage;

generating an ultraviolet (UV) laser beam;

imaging the UV laser beam onto the workpiece;

propelling a fine spray of liquid onto the workpiece during exposure of the workpiece to the UV laser beam, wherein the liquid is not substantially photoabsorbing around a primary UV wavelength of the UV laser beam; and

translating the workpiece on the translation stage relative to the UV laser beam in at least two dimensions that are substantially in a plane of the workpiece, such that by translating the stage, a substantial surface area of the workpiece may be machined by exposure to the incident UV laser beam.

22. The method of Claim 21, wherein the fine spray of liquid is propelled directly at the workpiece.

23. The system of Claim 21, wherein the fine spray of liquid becomes a mist as the liquid settles onto the workpiece.

24. The method of Claim 21, wherein the liquid substantially comprises water.

25. The method of Claim 21, wherein the imaging step include focusing the UV laser beam at the workpiece.

26. The method of Claim 21, wherein the fine spray of liquid is propelled so that it becomes a thin layer of the liquid flowing over an application region of the workpiece.

27. The method of Claim 26, wherein the thin layer is less than 100 microns thick.

28. The method of Claim 26, wherein the thin layer is between 25 and 60 microns thick.

29. The method of Claim 26, wherein the thin layer is between 25 and 50 microns thick.

30. The method of Claim 26, wherein the thin layer just thick enough to be maintained as a continuous sheet of liquid over the application region of the workpiece.

31. The method of Claim 26, wherein the application region comprises a few square millimeters of surface area of the workpiece.

32. The method of Claim 26, wherein the thin layer flows at a flow rate of around one milliliter per minute.

33. The method of Claim 21, wherein the propelling step including coupling a propellant with the liquid for assisting in the propelling of the fine spray of the liquid.

34. The method of Claim 33, wherein the propellant includes a pressurized gas that is not substantially photoabsorbing around a primary UV wavelength of the UV laser beam.

35. The method of Claim 34, wherein the pressure of the pressurized gas is between 5 and 100 psi.

36. The method of Claim 34, wherein the pressure of the pressurized gas is around 18 psi.

37. The method of Claim 21, wherein the propelling step includes propelling the liquid through a nozzle defining an orifice between 100 and 1000 microns across.

38. The method of Claim 37, wherein the nozzle defines an orifice around 300 microns across.

39. The method of Claim 21, further comprising the step of drawing the liquid from the workpiece.

40. The method of Claim 21, further comprising the step of collecting the liquid as it runs off of the workpiece.

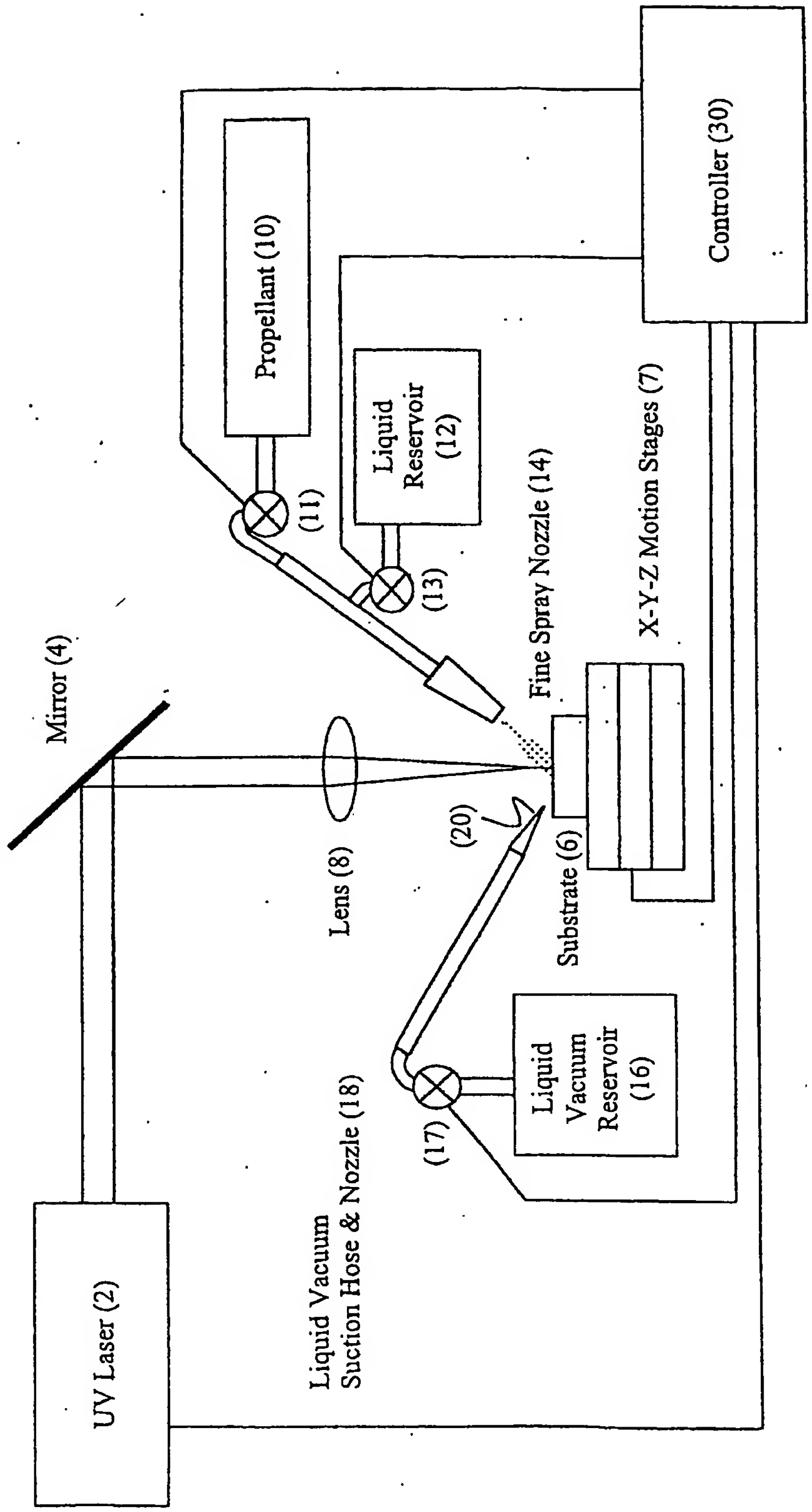

Figure 1: Laser Liquid Assist Apparatus

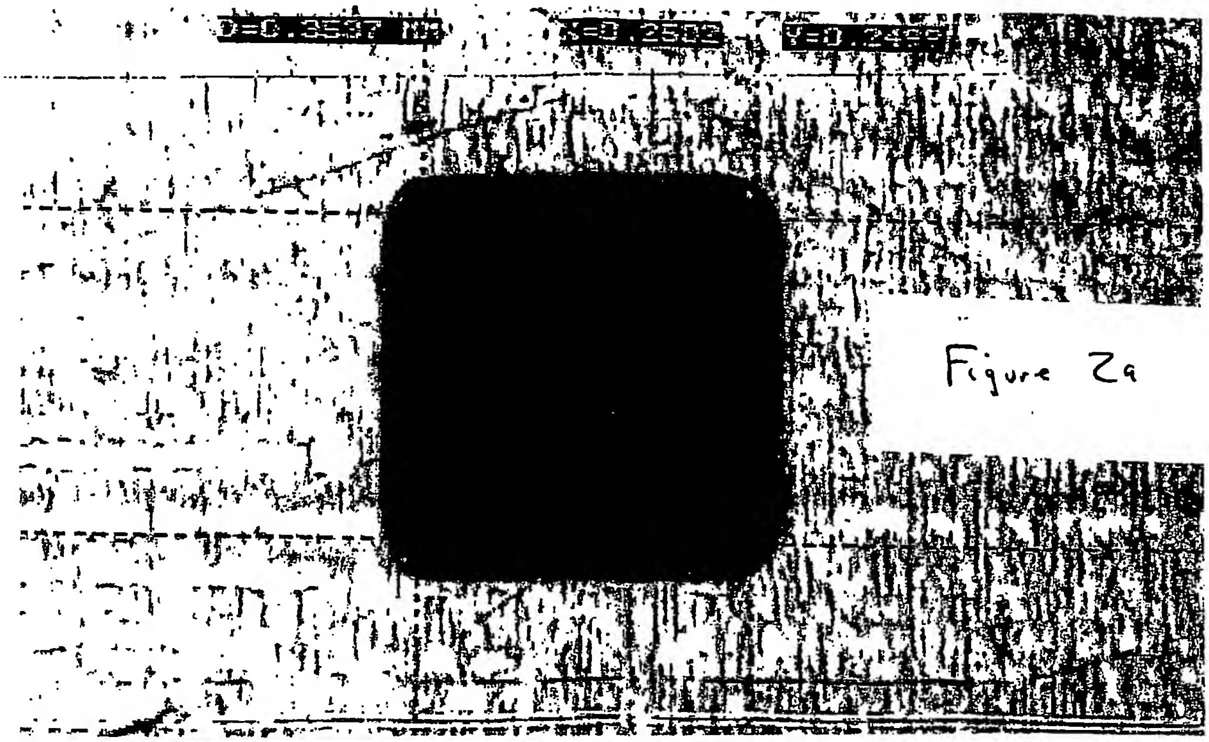

Figure 2a

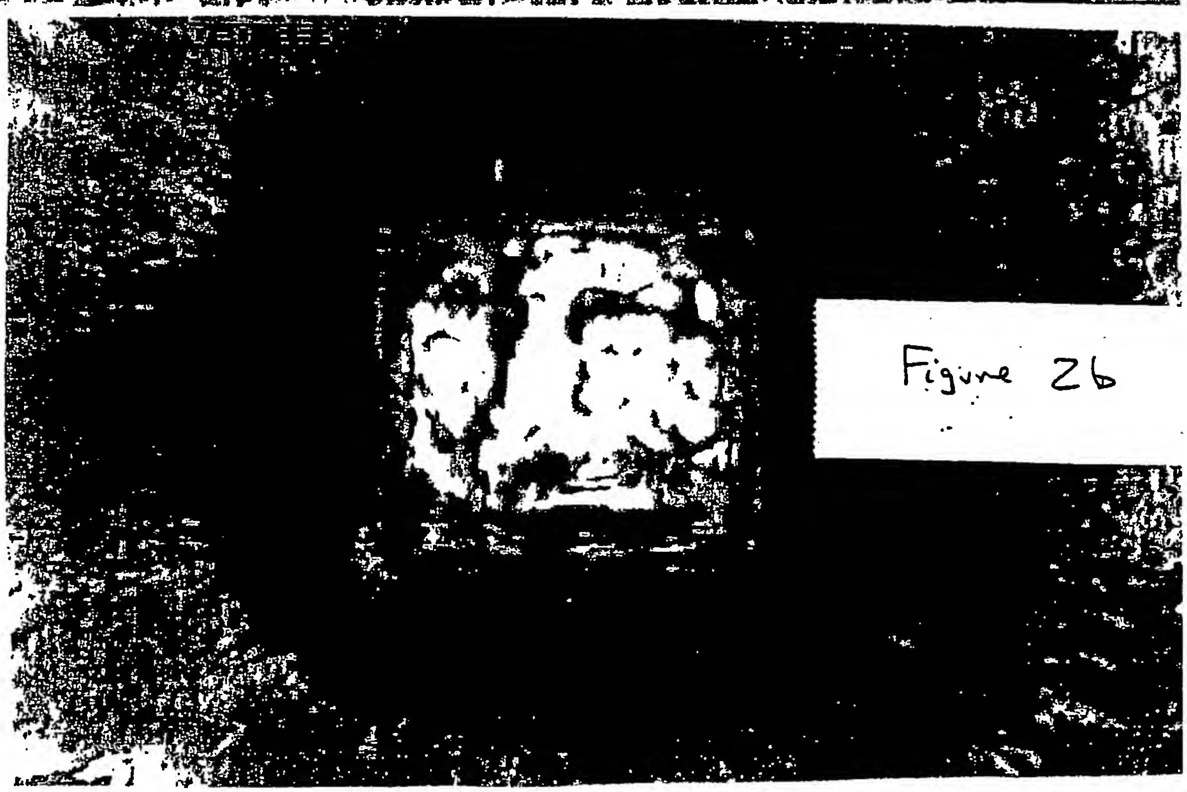

Figure 2b

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/31428

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :B23K 26/12, 26/40
US CL : 219/121.7, 121.71, 121.86
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 219/121.7, 121.71, 121.86,121.84

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 6,217,422 B1 (FRANCA et al.) 17 April 2001 (17/04/2001), see entire document.	1-40
Y	JP 59-206,189 A (ISHIWAKA) 21 November 1984, (21/11/84), see entire document.	1-40
Y	JP 10-99,978 A (TOUJIYOU) 21 April 1998 (21/04/98), see entire document.	1-40

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
28 JANUARY 2003

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